Light-Flavor Hadron Production from Small to Large Collision Systems at ALICE

A. G. Knospe

The University of Houston

on behalf of the ALICE Collaboration

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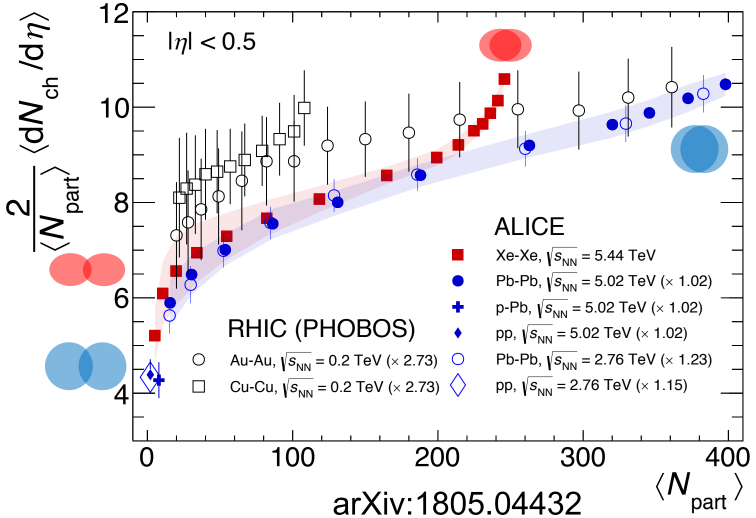
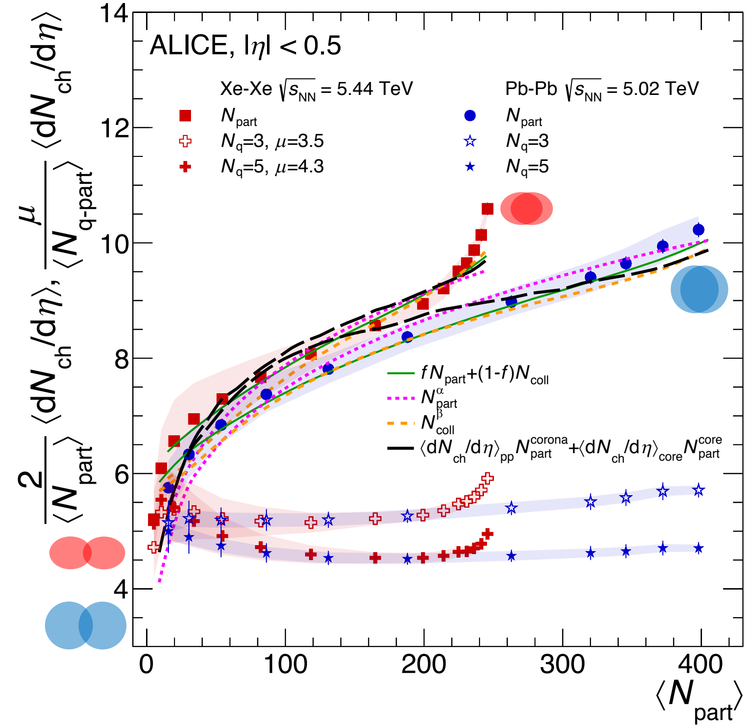
Charged-Particle Multiplicity

- N_{part} scaling violated: factor of ≈2 increase from peripheral to central A–A at LHC energies
- Quark-Glauber parameterization
  - Wounded constituent quarks
  - *PRC* **67** 064905 (2003), *PRC* **94** 024914 (2016)
  - $N_{q\text{-}part}$ scaling with N_q=3 or 5
- 0-5% Xe–Xe: more charged-particle production than mid-central Pb–Pb (similar N_{part})
  - Not explained by participant-quark scaling
  - Not fully reproduced by models
  - Hint of similar behavior at RHIC (Cu–Cu & Au–Au)

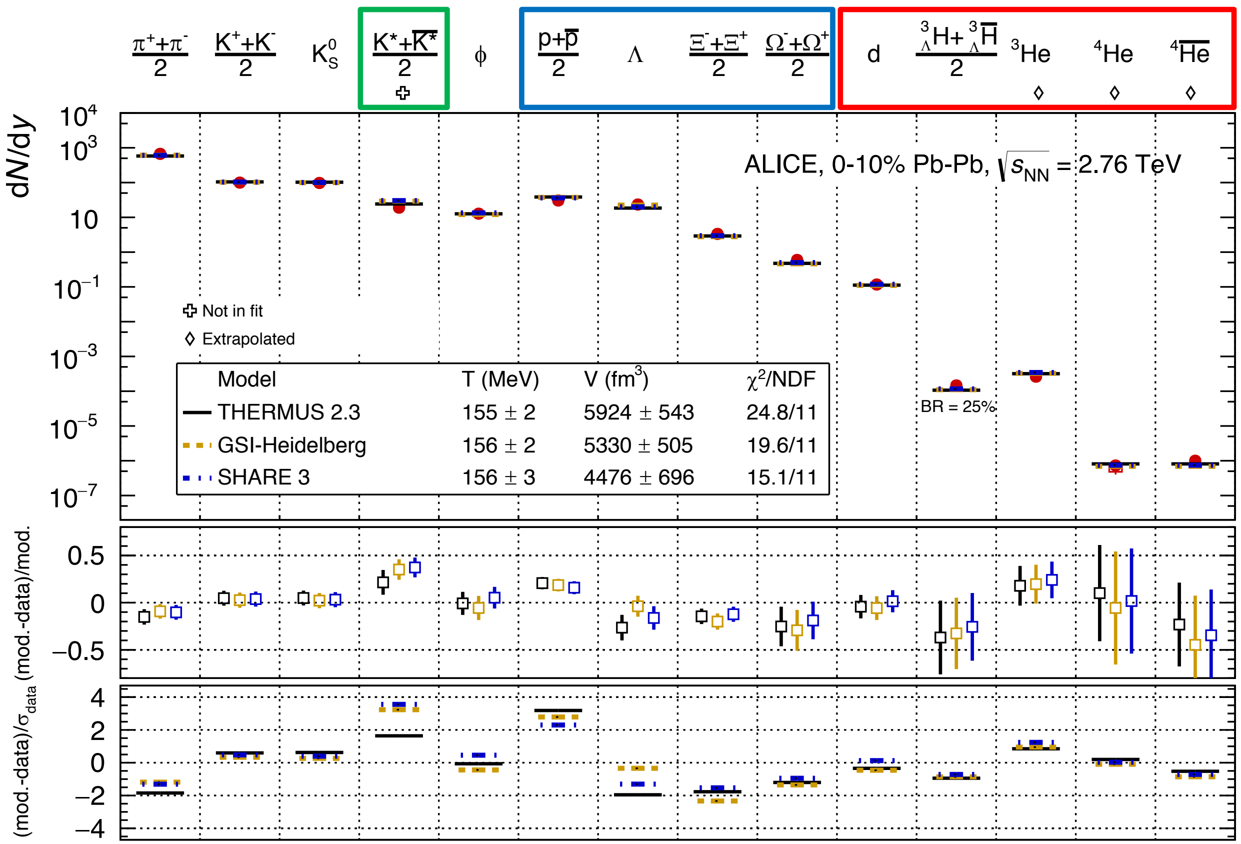


arXiv:1805.04432



Thermal Models

- Most light-flavor hadron yields described fairly well by thermal models with single chemical freeze-out temp. (T_{ch}=156±3 MeV for Pb–Pb at 2.76 TeV)
- Even (anti)nuclei and hyper-nuclei are described
- Short-lived resonances (e.g., K^{*0}) deviate due to re-scattering effects (excluded from fit)
- However, some tension for protons and (multi)strange baryons



Additional effects needed?
Baryon annihilation, interacting hadron gas, incomplete hadron spectrum?

Nucl. Phys. A **971** 1-20 (2018)
THERMUS: Wheaton *et al.*, *Comput. Phys. Commun.* **180** 84 (2009)
GSI-Heidelberg: Andronic *et al.*, *PLB* **673** 142 (2009)
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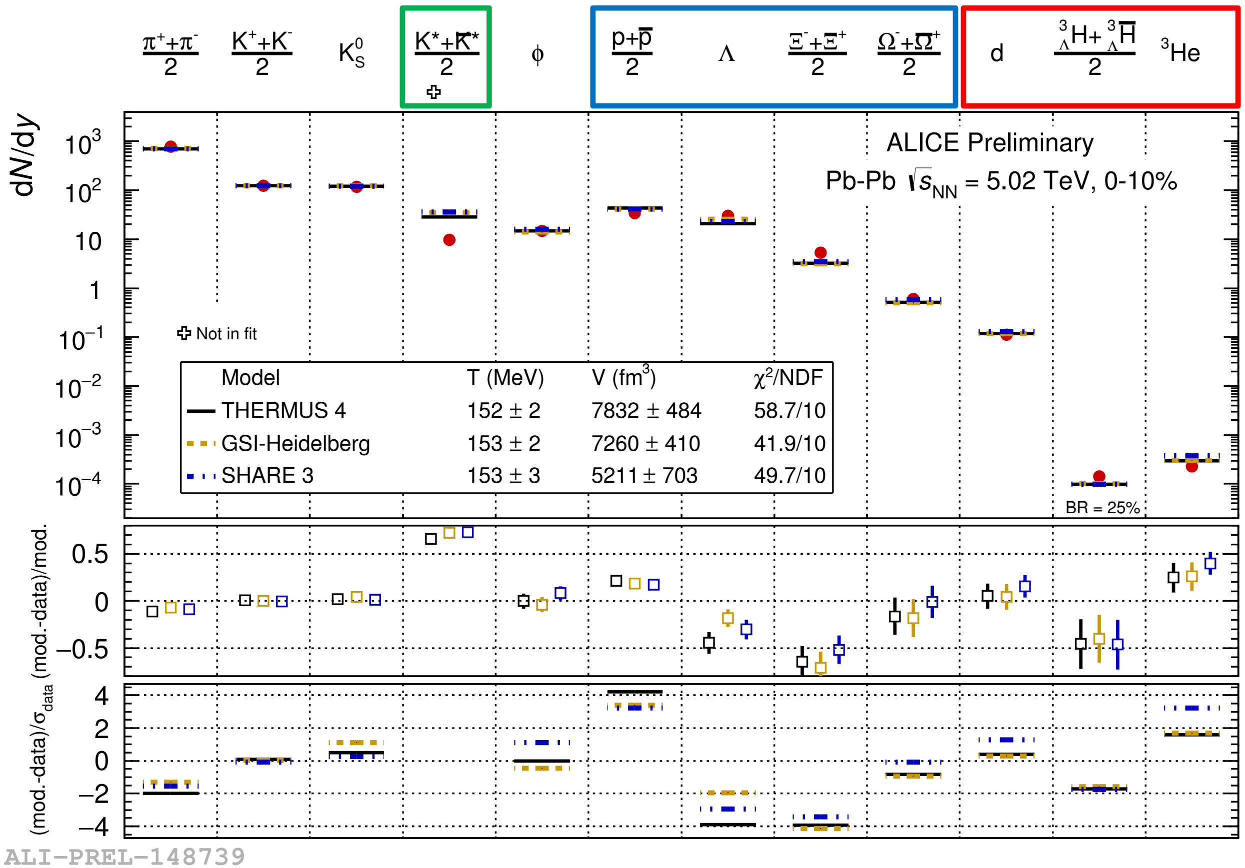

Model	T (MeV)	V (fm³)	χ²/NDF
THERMUS 4	152 ± 2	7832 ± 484	58.7/10
GSI-Heidelberg	153 ± 2	7260 ± 410	41.9/10
SHARE 3	153 ± 3	5211 ± 703	49.7/10

Additional effects needed?
Baryon annihilation, interacting hadron gas, incomplete hadron spectrum?

Similar behavior seen for Pb–Pb at 5.02 TeV:
T_{ch}=153±3 MeV

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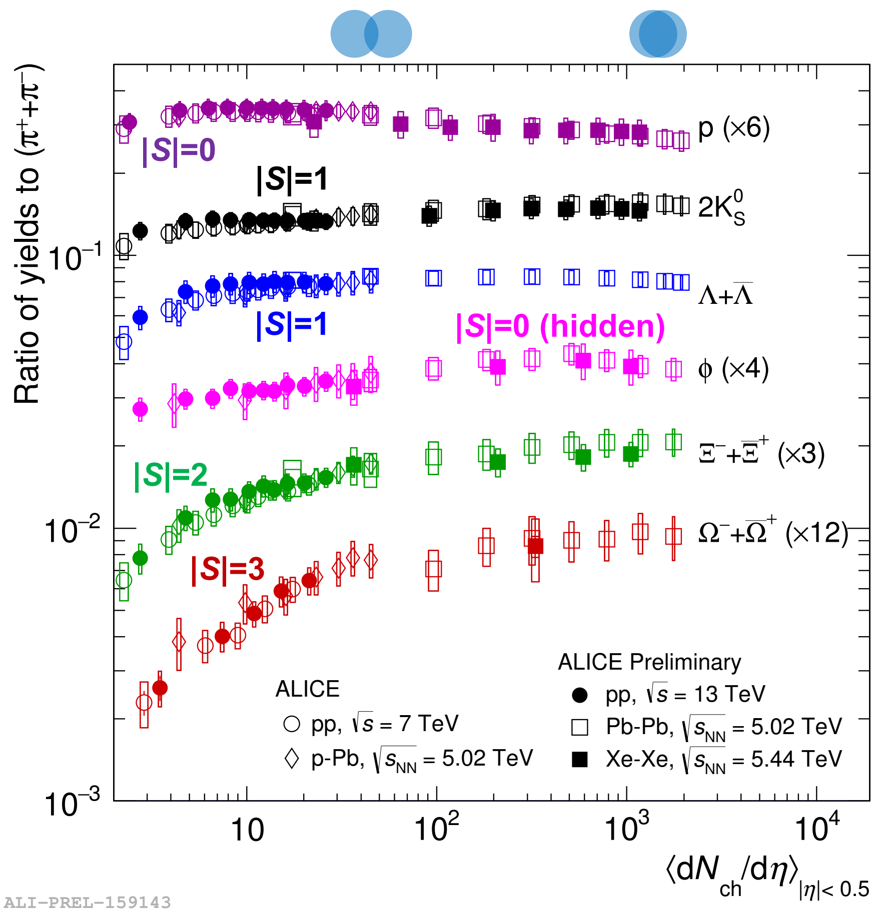
Strangeness Production

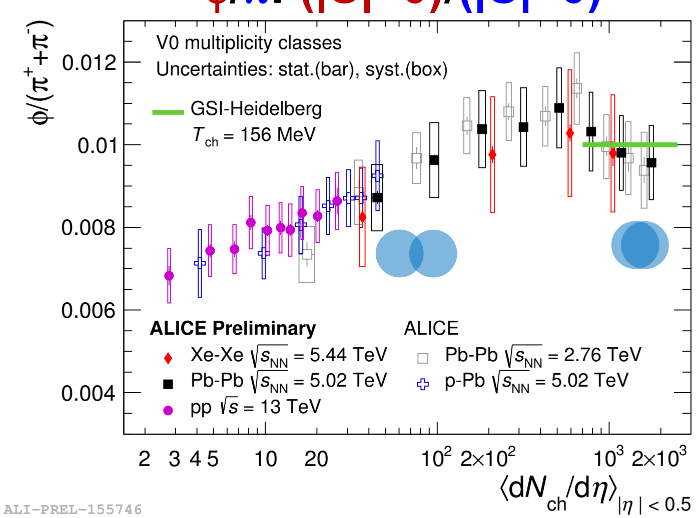
- Smooth evolution of particle production with charged-particle multiplicity across pp, p–Pb, Xe–Xe, and Pb–Pb collisions
  - No energy dependence
  - Hadron chemistry is driven by the multiplicity (system size)
- Increase of strange-particle production for small systems, saturation around thermal-model values for large systems
  - Magnitude of strangeness enhancement increases with strange-quark content



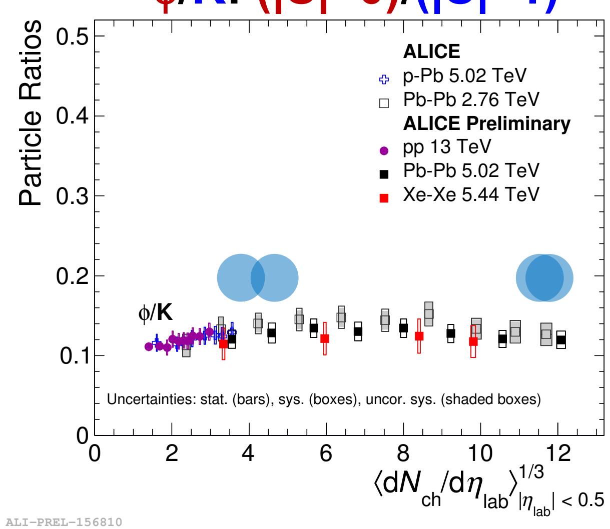
Hadron Chemistry: ϕ

- The ϕ meson ($s\bar{s}$) has hidden strangeness and is a key probe in studying strangeness production
  - Particles with open strangeness are subject to canonical suppression in small systems, while ϕ is not
- Large systems: ϕ production described by thermal models
- Small systems: increase in ϕ/π ratio with multiplicity
  - Not expected for simple canonical suppression
  - Favors non-equilibrium production (γ_s) production of ϕ or all strange particles
- Ratios ϕ/K and Ξ/ϕ fairly flat across wide multiplicity range
  - The ϕ has "effective strangeness" of 1–2 units

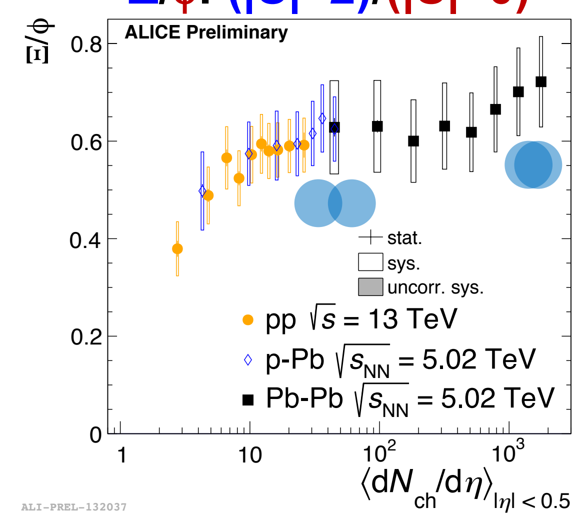
ϕ/π: (|*S*|=0)/(|*S*|=0)



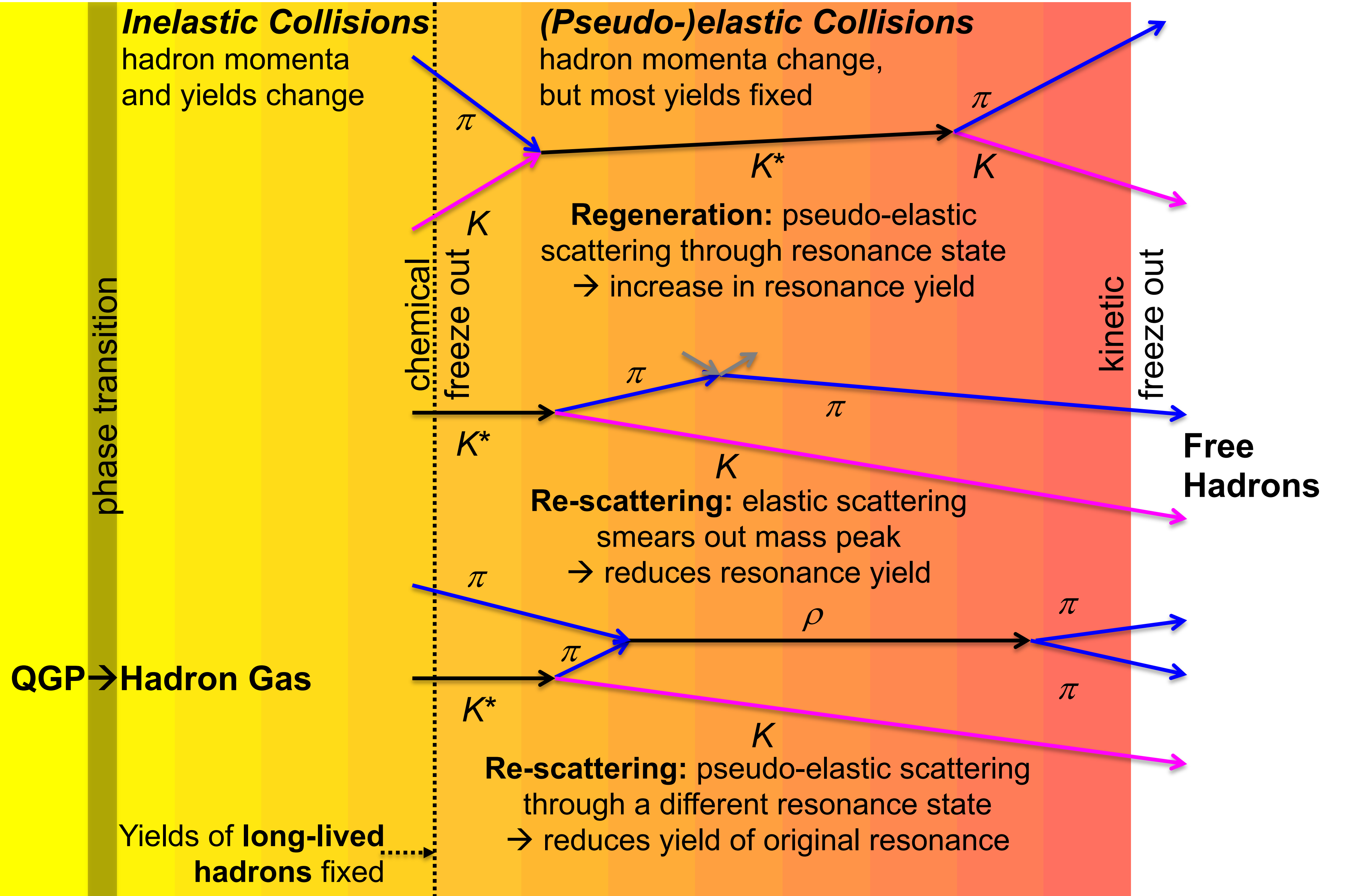
ϕ/K: (|*S*|=0)/(|*S*|=1)



Ξ/ϕ: (|*S*|=2)/(|*S*|=0)

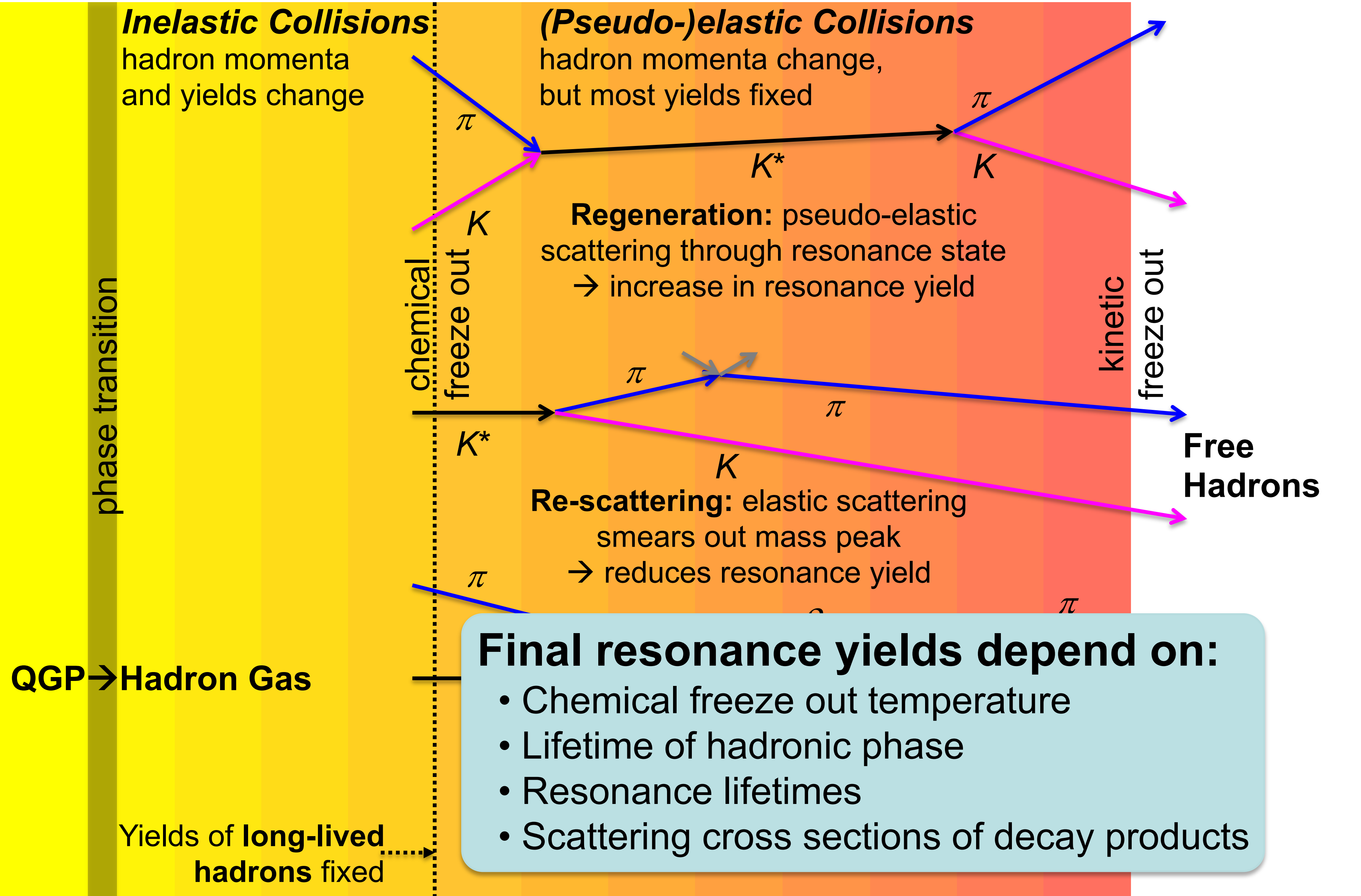


Resonances


Inelastic Collisions
hadron momenta and yields change
(Pseudo-)elastic Collisions
hadron momenta change, but most yields fixed
phase transition
chemical freeze out
kinetic freeze out
π
K
K*
π
K
Regeneration: pseudo-elastic scattering through resonance state
→ increase in resonance yield
π
π
K*
K
Re-scattering: elastic scattering smears out mass peak
→ reduces resonance yield
Free Hadrons
π
π
ρ
π
π
QGP→Hadron Gas
K*
K
Re-scattering: pseudo-elastic scattering through a different resonance state
→ reduces yield of original resonance
Yields of long-lived hadrons fixed

Resonances

Knospe

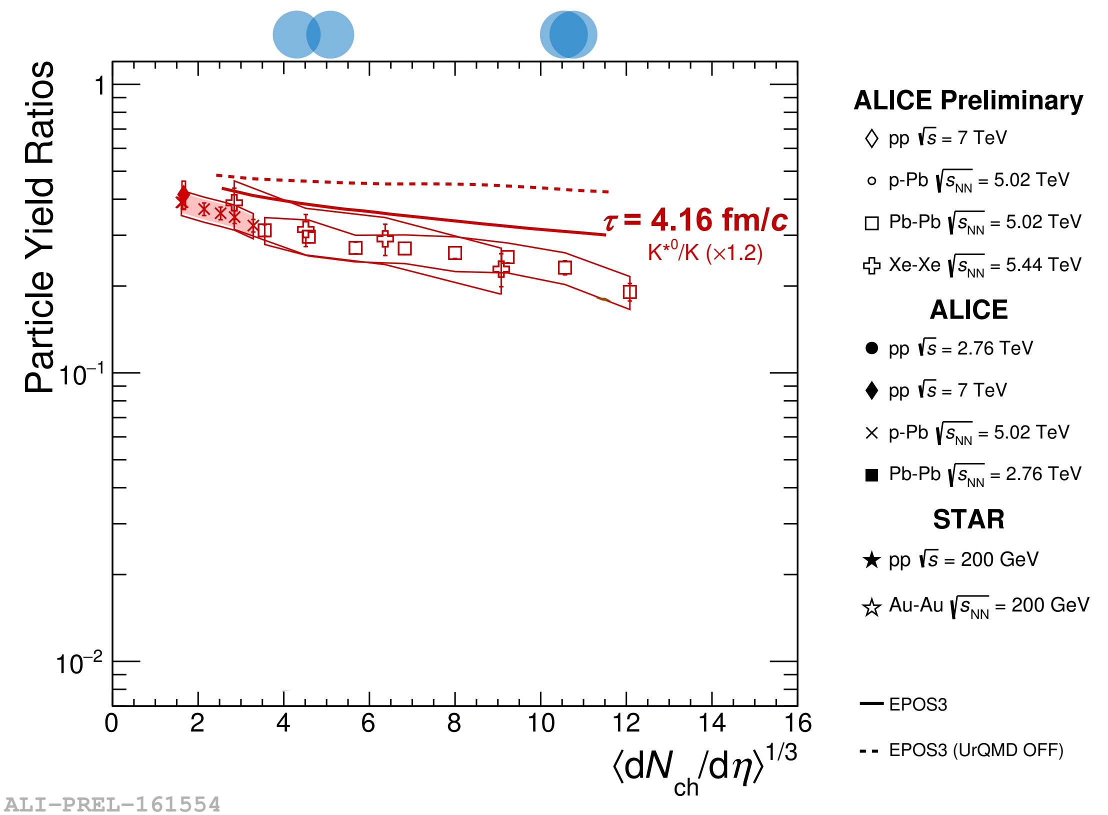


Final resonance yields depend on:

- Chemical freeze out temperature
- Lifetime of hadronic phase
- Resonance lifetimes
- Scattering cross sections of decay products

Resonance Suppression

- Suppression of K*⁰ w.r.t. pp and thermal model values
  - Re-scattering of decay products in hadronic medium
  - Hint of K*⁰ suppression in high-mult. pp and p–Pb



Resonance Suppression

- Suppression of K^{*0} w.r.t. pp and thermal model values
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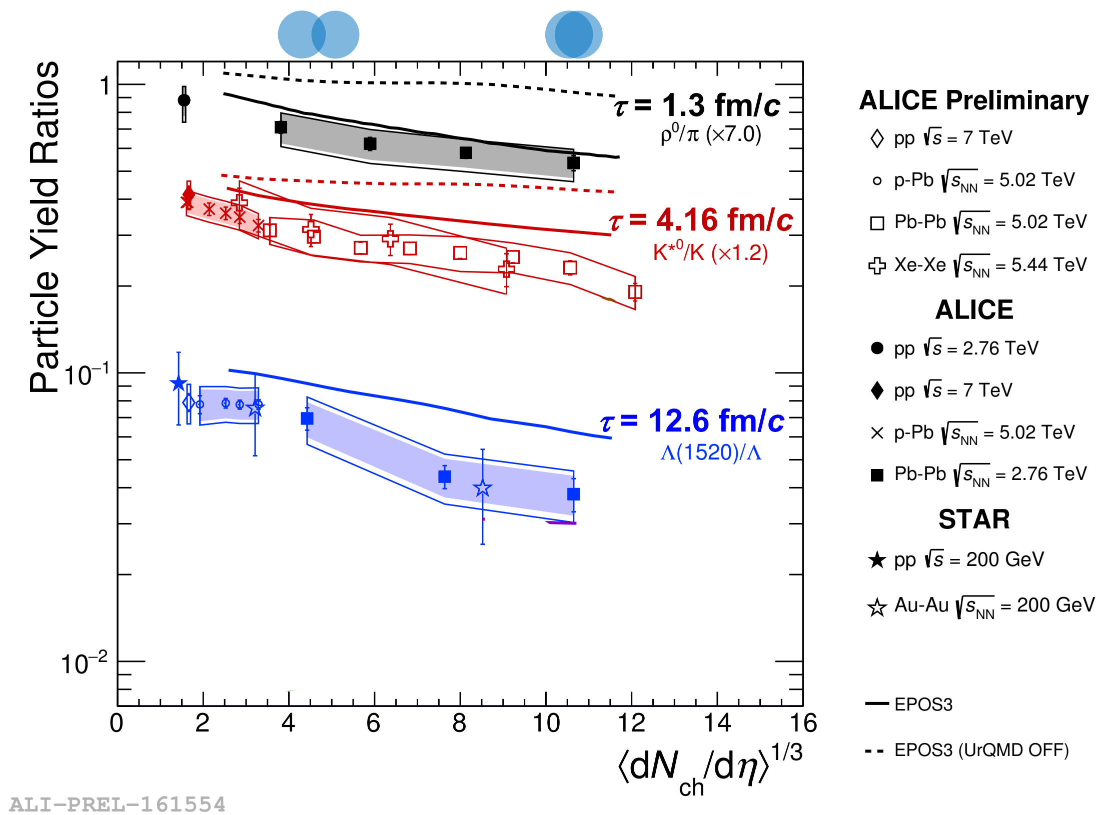
  - Hint of K^{*0} suppression in high-mult. pp and p–Pb
- Similar suppression of ρ^0 & $\Lambda(1520)$



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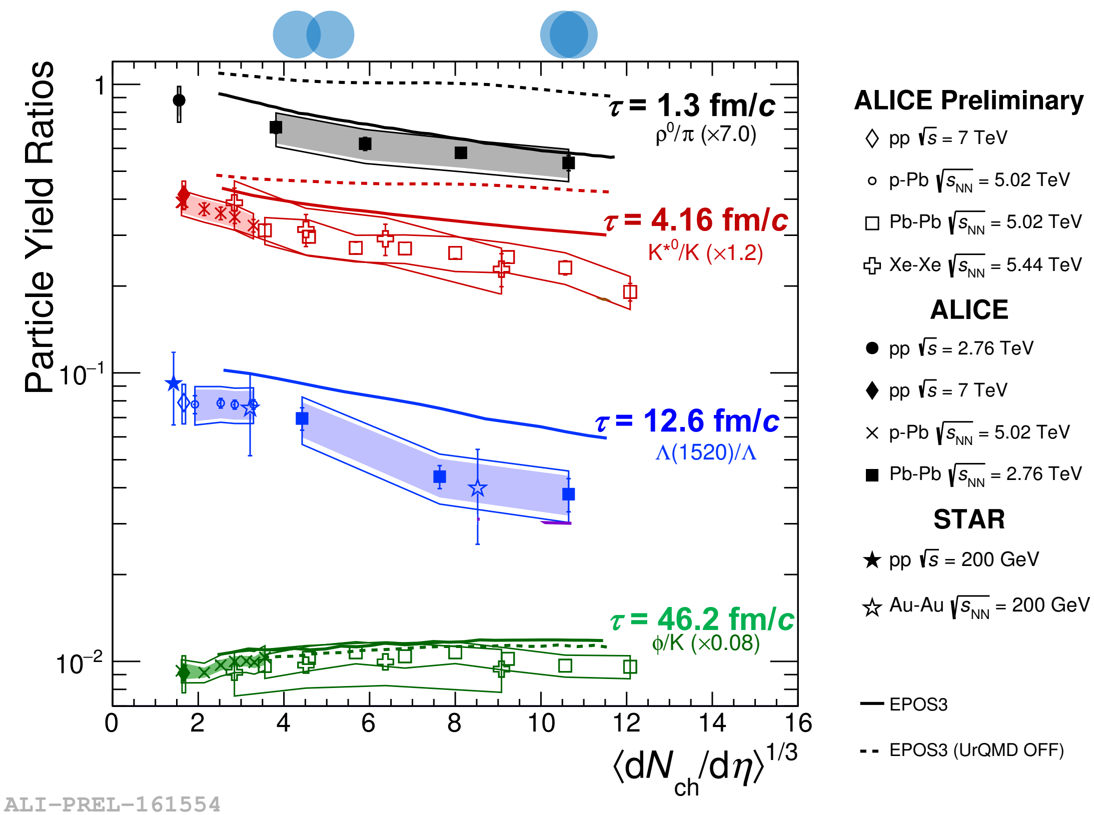
- No ϕ suppression: lives longer, decays outside fireball



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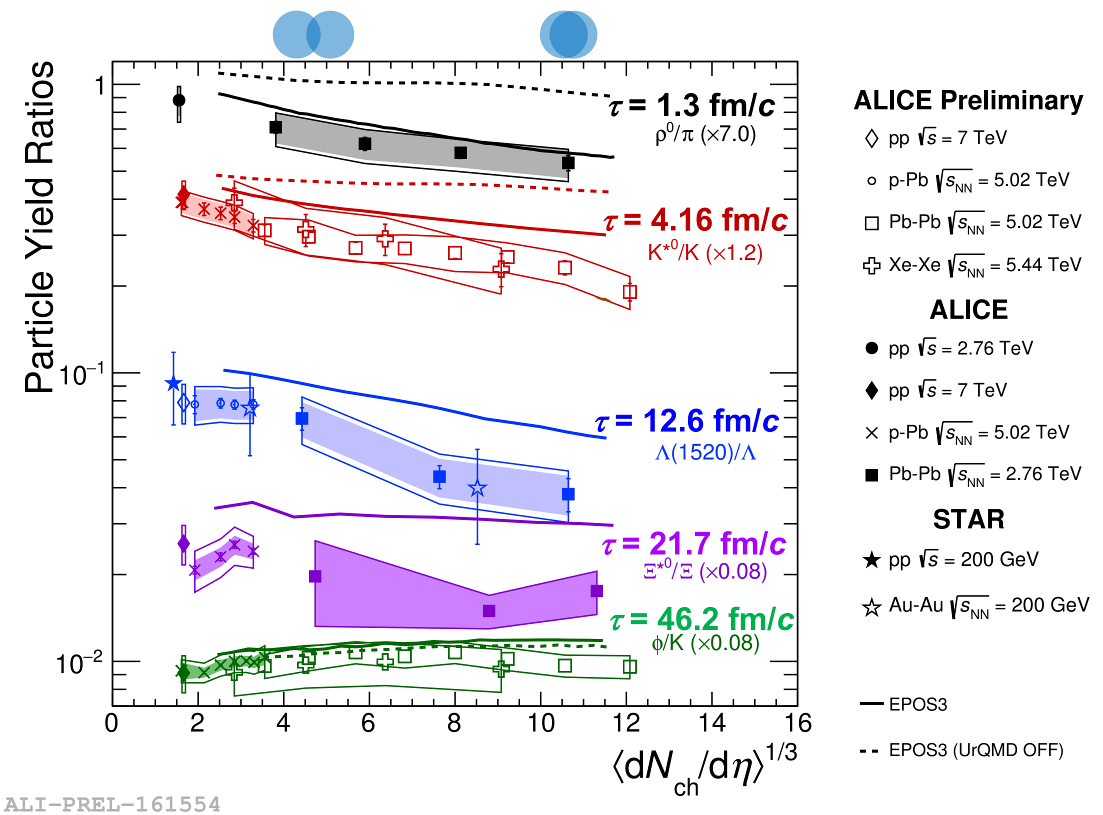

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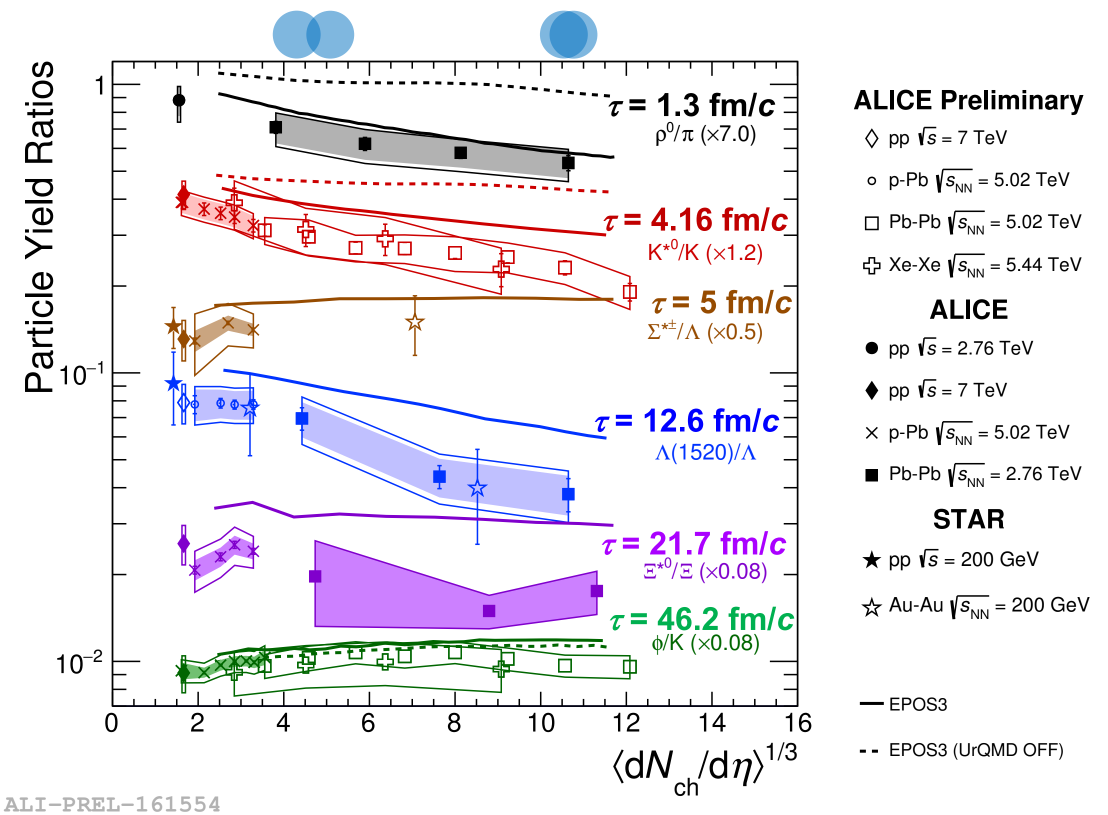
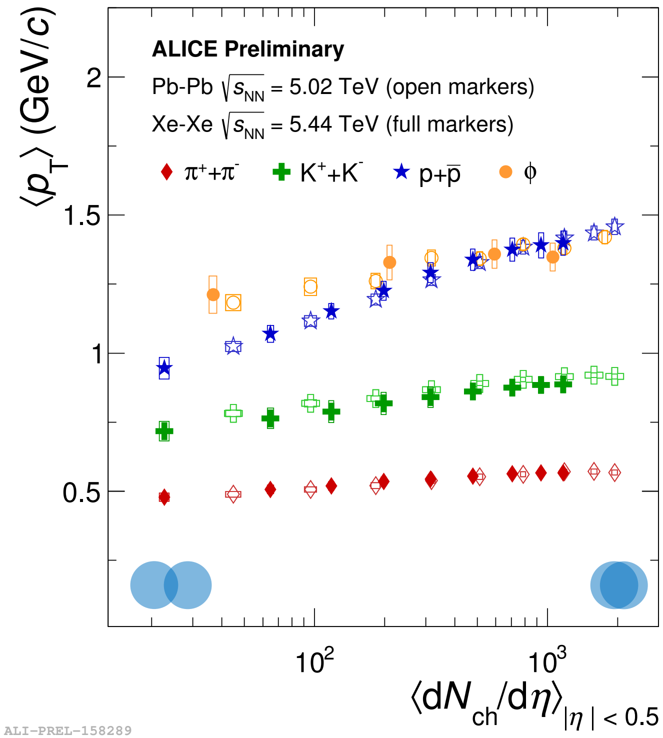
- Similar suppression of ρ^0 & $\Lambda(1520)$
- No ϕ suppression: lives longer, decays outside fireball
- Possible weak suppression of Ξ^{*0} w.r.t. pp collisions
- No measurement of $\Sigma^{*\pm}/\Lambda$ in Pb–Pb yet
- Ratios do not depend on energy (RHIC→LHC) or collision system (same for p–Pb and Xe–Xe)
- Trends qualitatively described by EPOS
  - Includes scattering effects modeled with UrQMD



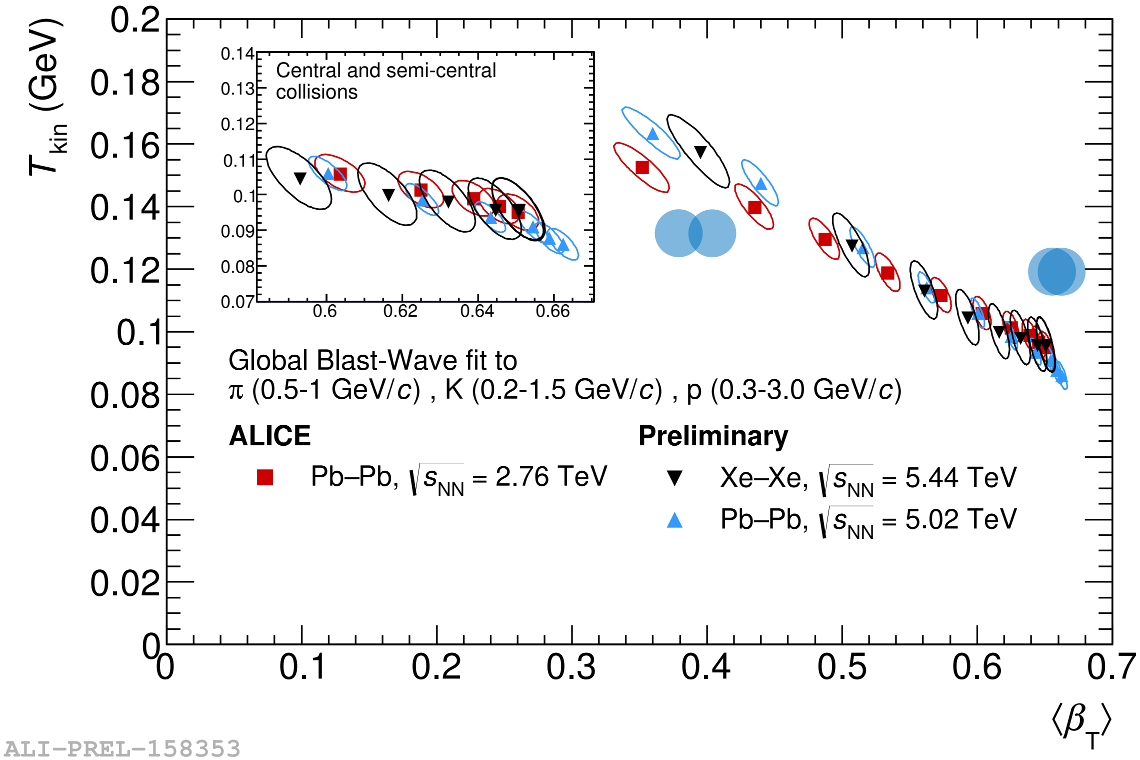
Mean Transverse Momentum

- Unidentified charged hadrons
  - Only small differences (~3%) between Pb–Pb and Xe–Xe
  - Consistent with predictions from hydrodynamic model
- Identified hadrons:
  - Mass ordering of $\langle p_T \rangle$ (see p and ϕ, which have similar masses)
  - Mass ordering breaks down for peripheral A–A, p–Pb and pp



Blast-Wave Fits

- Simultaneous blast-wave fits of $\pi^{\pm}$, $K^{\pm}$, & p p_{T} spectra
- A–A collisions
  - T_{kin} decreases and transverse flow velocity $\langle \beta_{T} \rangle$ increases w/ centrality
  - Xe–Xe and Pb–Pb consistent



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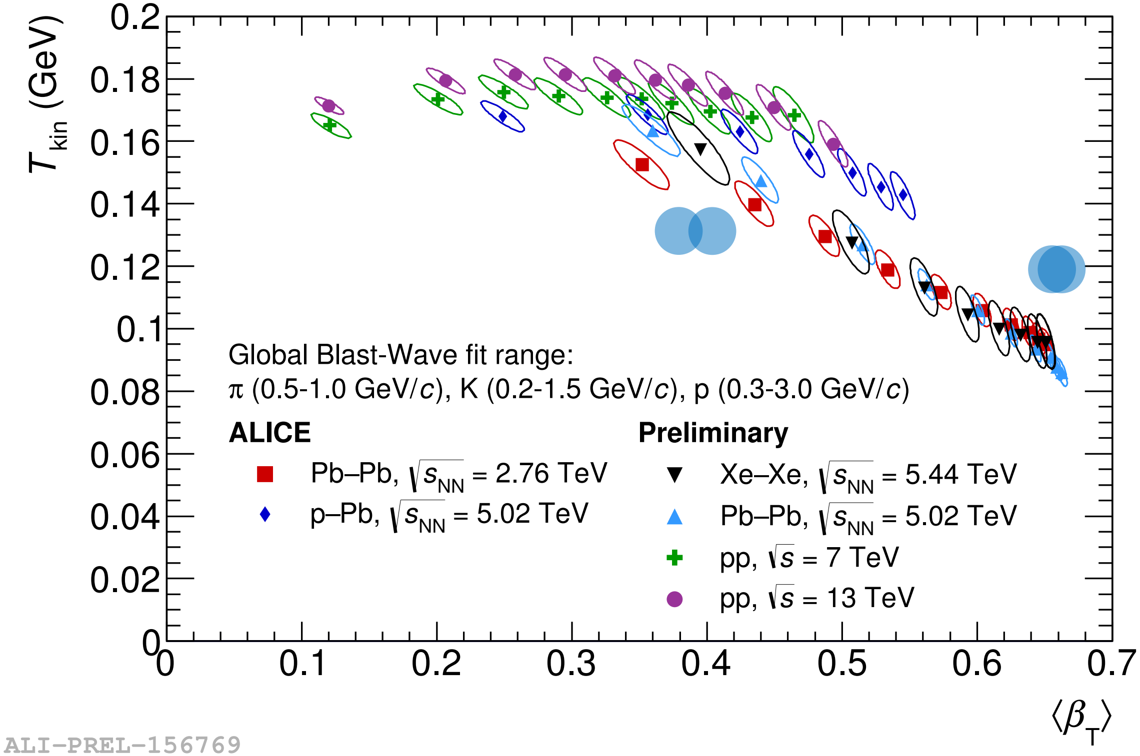
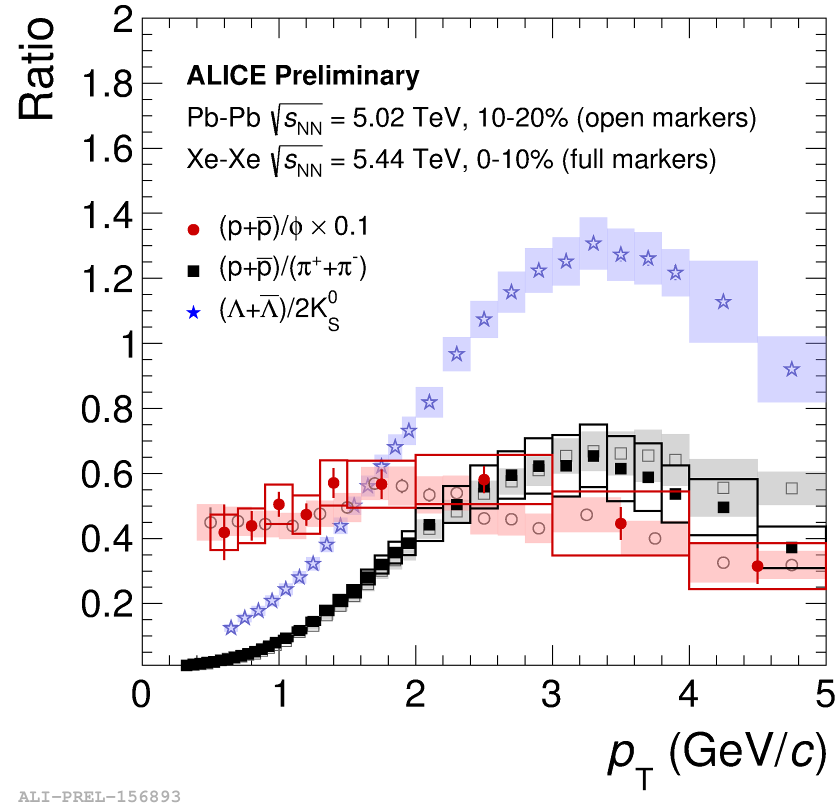
- A–A collisions
  - T_{kin} decreases and transverse flow velocity $\langle \beta_T \rangle$ increases w/ centrality
  - Xe–Xe and Pb–Pb consistent
- Small systems
  - Similar evolution of parameters for pp and p–Pb
  - For similar multiplicities: $\langle \beta_T \rangle$ (and $\langle p_T \rangle$) greater in smaller systems



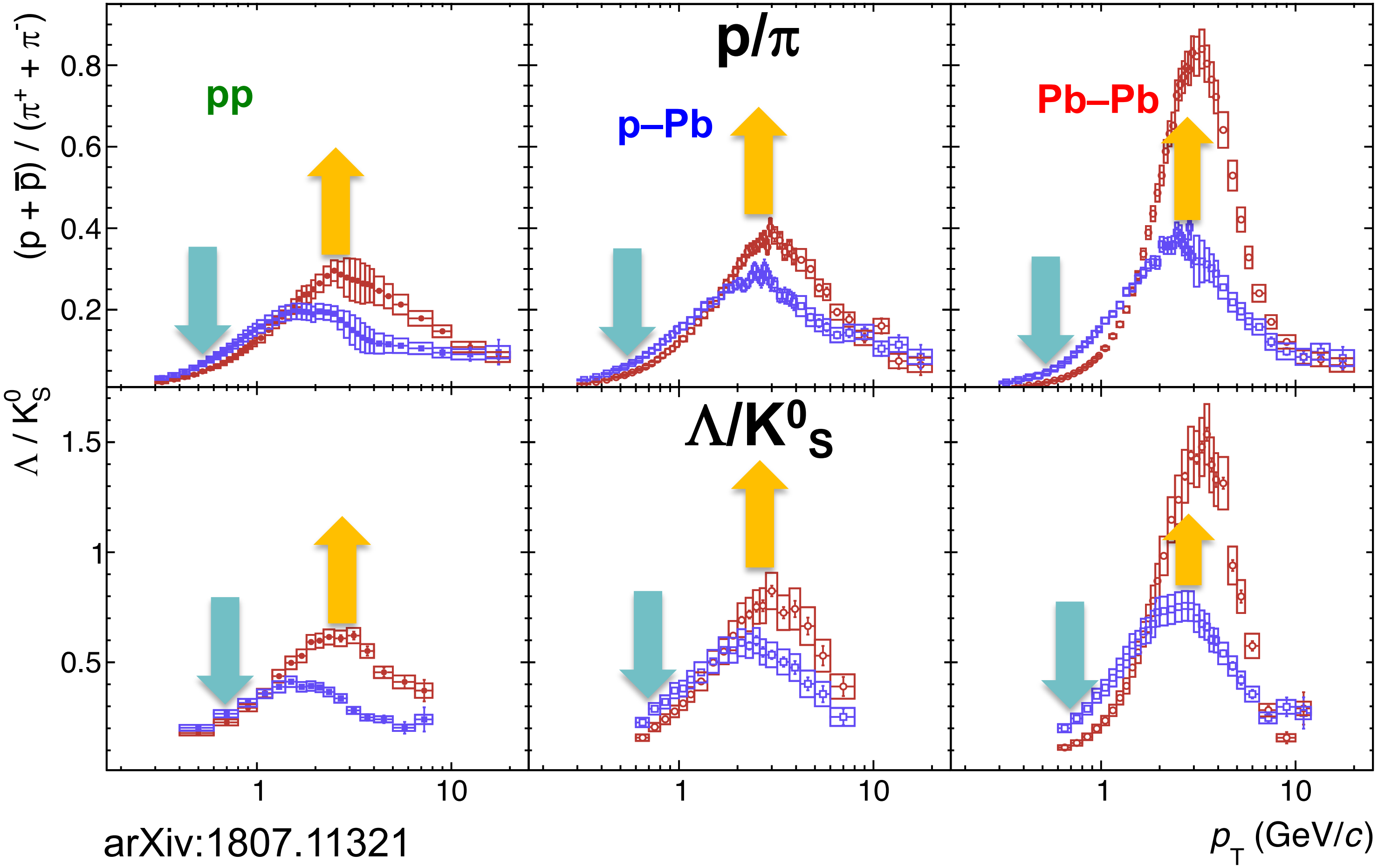
Baryon-to-Meson Ratios

- Baryon-to-meson ratios vs. p_T allow us to study the interplay of hydrodynamics and recombination
- Compare Xe–Xe & Pb–Pb: consistent results for similar multiplicities
- p/ϕ ratio is useful: baryon and meson with almost the same mass
  - Flat with p_T → consistent with hydrodynamic behavior, but can also be described by some recombination models
    [V. Greco et al, *PRC* **92** 054904 (2015)]



Baryon/Meson Ratios

- From low multiplicity (peripheral) to high multiplicity (central):
  - Baryon/Meson ratios depleted at low p_T
  - Enhanced at intermediate p_T
- Qualitative similarities between pp, p–Pb, & Pb–Pb



arXiv:1807.11321

Baryon/Meson Ratios

- Baron/meson ratios in different p_T regions:
  - Low-p_T depletion and intermediate-p_T enhancement
- Similar behavior for the three systems

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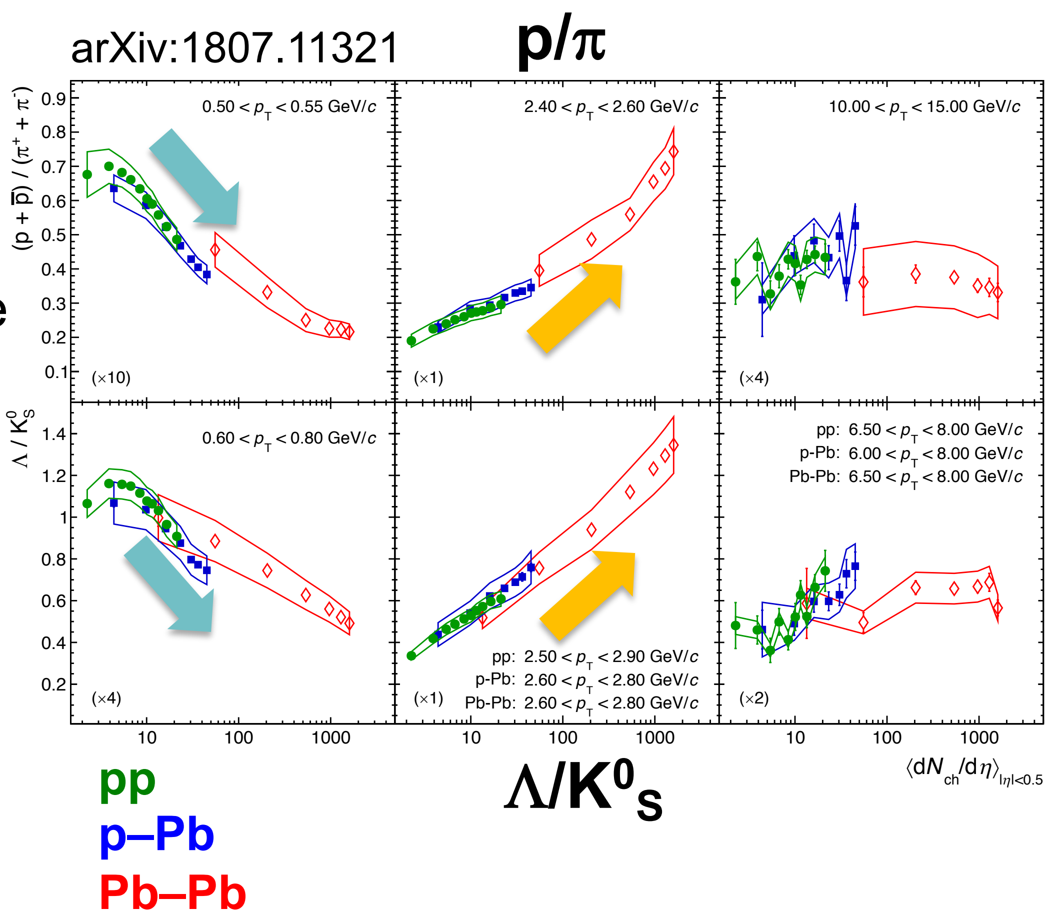
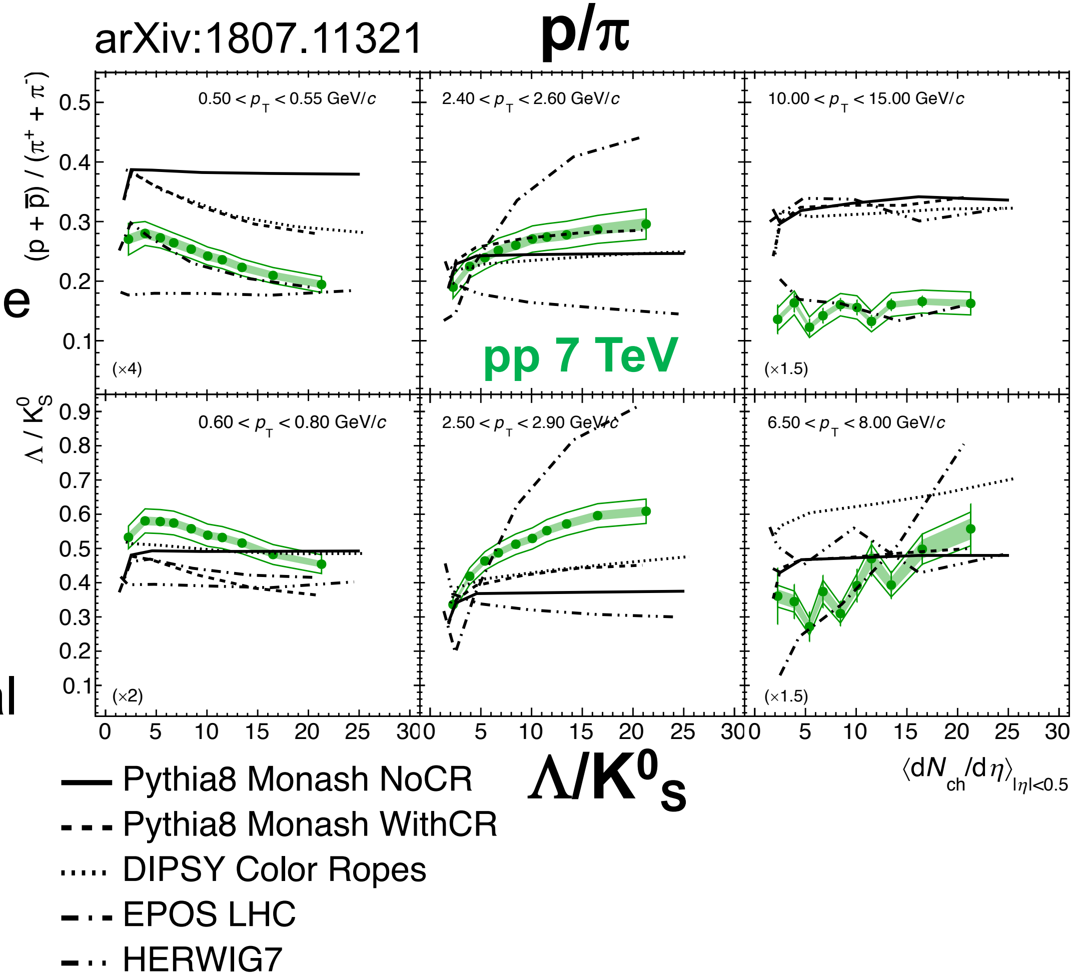


Baryon/Meson Ratios

- Baron/meson ratios in different p_T regions:
  - Low-p_T depletion and intermediate-p_T enhancement
- Similar behavior for the three systems
- Trend in pp described qualitatively by color reconnection (PYTHIA) and color ropes (DIPSY); over-predicted by collective radial expansion in EPOS



Conclusions

- Charged-particle multiplicity
  - Follows $N_{\text{q-part}}$ scaling
  - Central Xe–Xe deviates from Pb–Pb for similar N_{part}
- Thermal models describe yields fairly well, but some tension w/ data
- Strangeness production evolves smoothly with multiplicity
  - No energy or collision-system dependence
  - ϕ yields evolve similar to particles w/ open strangeness, even in small systems.
- Suppression of ρ^0, K^{*0}, & $\Lambda(1520)$ resonances in central A–A colls.
  - Possible weak suppression of Ξ^{*0}
- p_T spectral shapes:
  - Evidence for hydro: mass ordering of $\langle p_T \rangle$ in central A–A
  - Xe–Xe results consistent with Pb–Pb for similar multiplicities
  - Enhancement in baryon/meson ratios at intermediate p_T for larger systems

Additional Material

Resonance Suppression

- Suppression of K^{*0} w.r.t. pp and thermal model values
  - Re-scattering of decay products in hadronic medium
  - Hint of K^{*0} suppression in high-mult. pp and p–Pb
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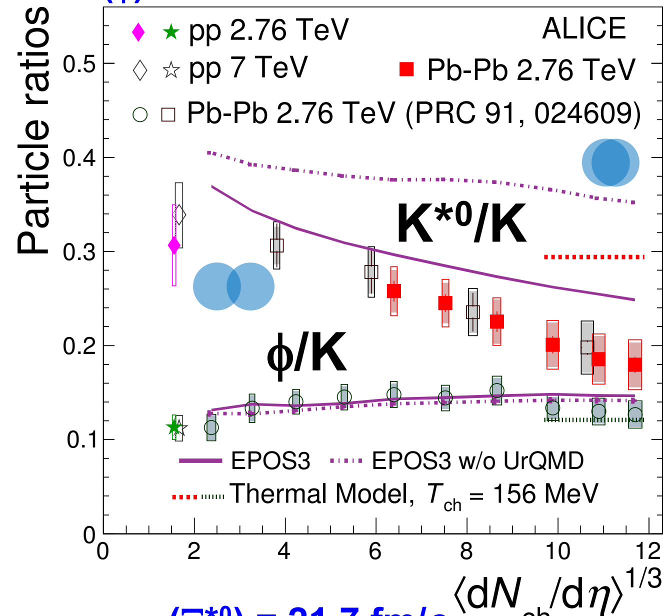
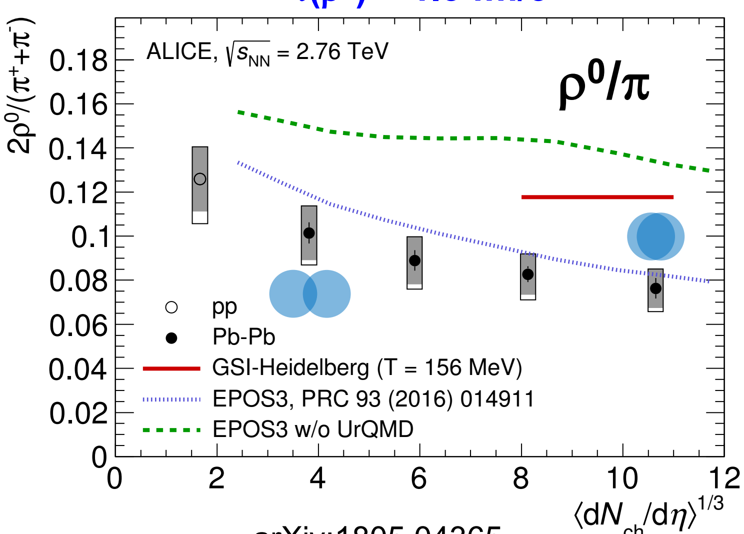
- Suppression trends qualitatively described by EPOS
  - Includes scattering effects modeled with UrQMD

$\tau(K^{*0})$ = 4.16 fm/c
$\tau(\phi)$ = 46.2 fm/c

PRC **95** 064606 (2017)

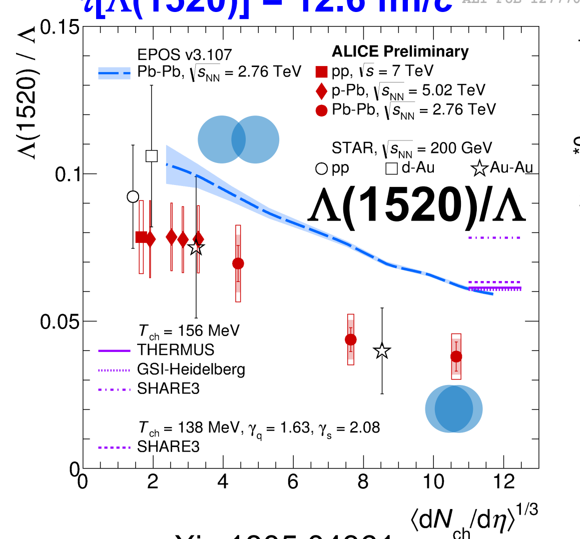


$\tau(\rho^0)$ = 1.3 fm/c



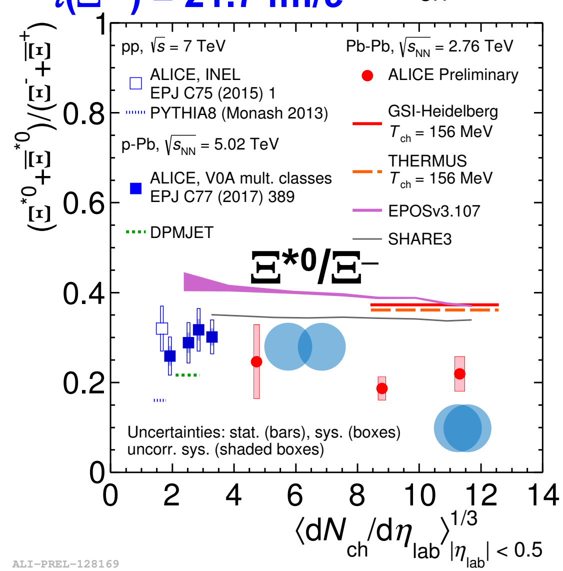
arXiv:1805.04365

$\tau[\Lambda(1520)]$ = 12.6 fm/c



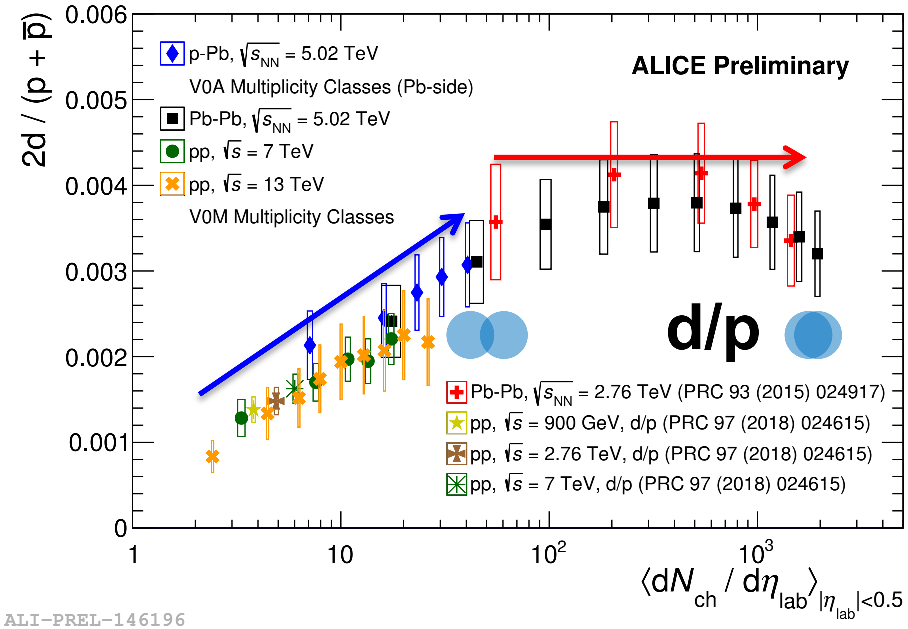
arXiv:1805.04361

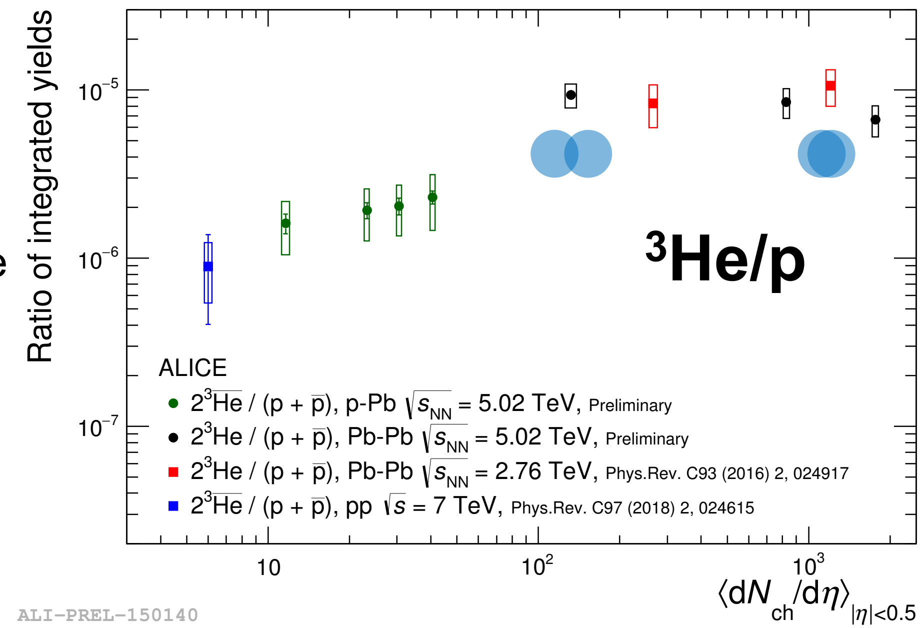
$\tau(\Xi^{*0})$ = 21.7 fm/c



Nuclei

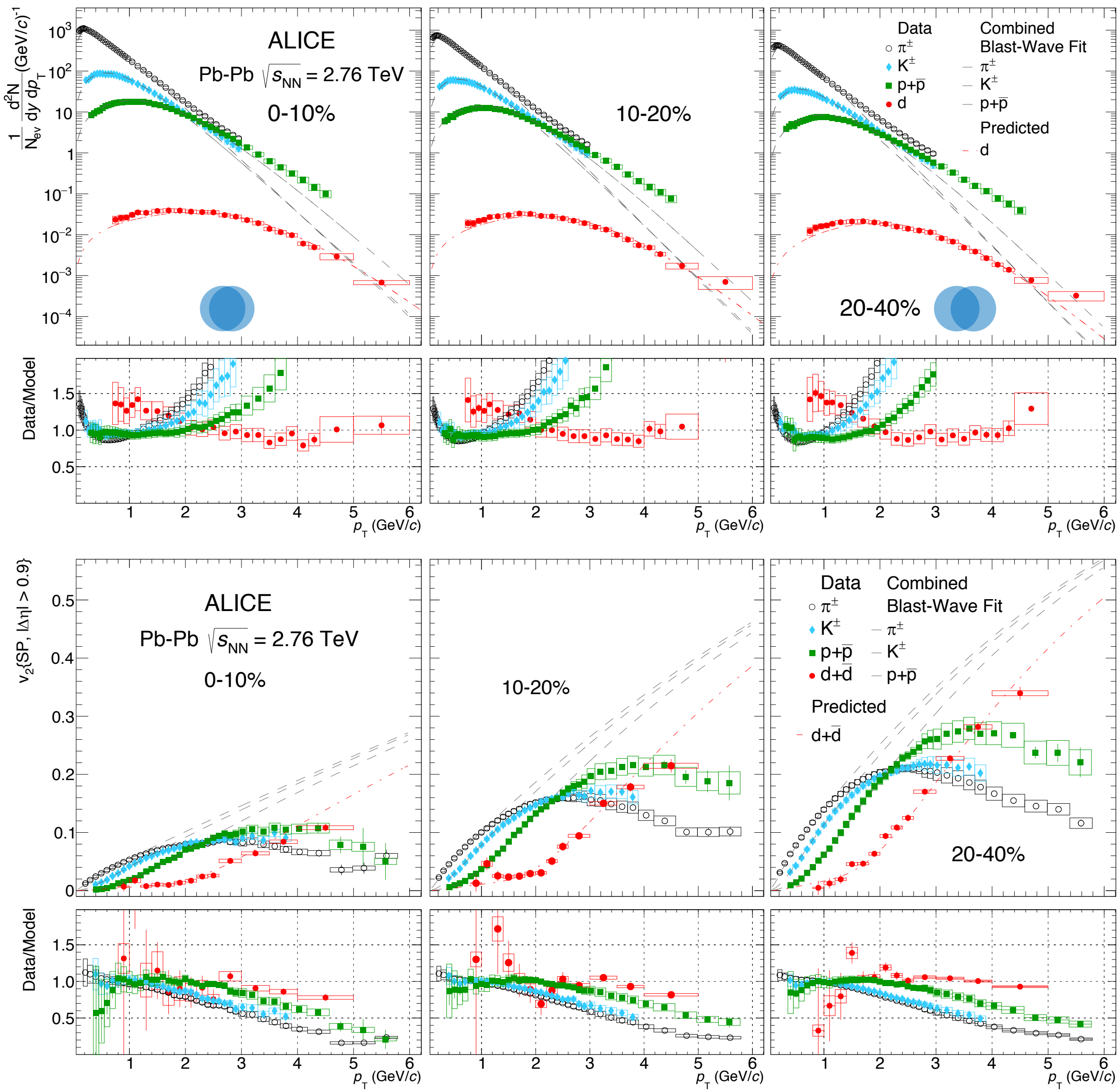
- Thermal models
  - Hadrons emitted in statistical equilibrium with chemical freeze-out temperature T_{ch}
  - Yields proportional to $\exp(-m/T_{ch})$
- Coalescence
  - Nuclei formed by baryons close in phase space after kinetic freeze-out
  - Nuclei may break up and re-form during hadronic phase
- Deuterons:
  - Coalescence in small systems and thermal production in A–A
  - Smooth transition between systems
  - Production controlled by system size
- ^{3}He: factor of 5 difference in ^{3}He/p ratio from p–Pb to Pb–Pb
  - But also a large gap in multiplicity
  - More data needed…





Deuterons

- Blast-wave model fit of $\pi^{\pm}K^{\pm}p$ p_T spectra and v_2 → predictions for deuterons
- Hint of common kinetic freeze-out for deuterons and lighter particles



ALICE, *EPJC* **77** 658 (2017)

Blast-Wave Model:

STAR, *PRL* **87** 182301 (2001)

E. Schnedermann *et al.*, *PRC* **48** 2462 (1993)

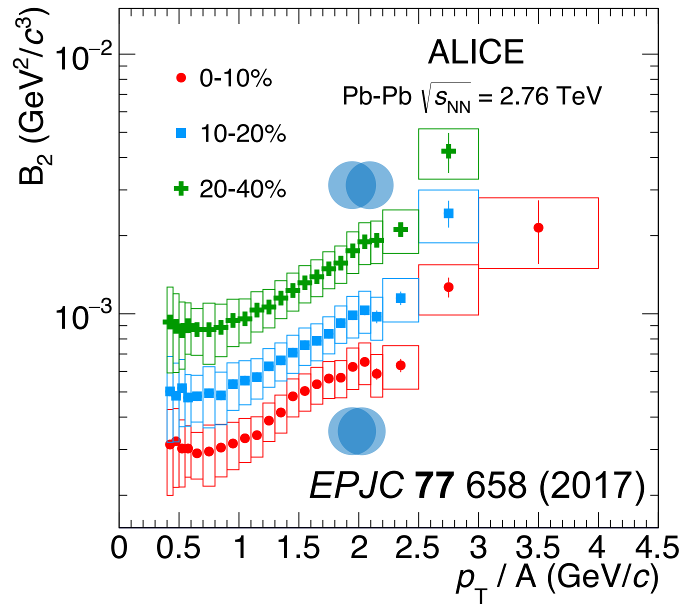
Deuteron Coalescence

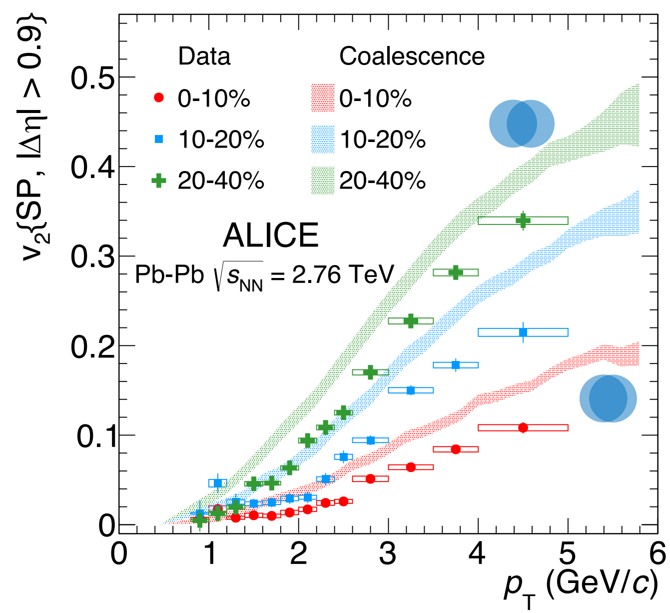
- Coalescence parameter for nucleus *i* with mass number *A*:

$$E_i \frac{d^3 N_i}{dp_i^3} = B_A \left(E_p \frac{d^3 N_p}{dp_p^3} \right)^A$$

$$B_2 = \frac{E_d \frac{d^3 N_d}{dp_p^3}}{\left(E_p \frac{d^3 N_p}{dp_p^3} \right)^2}$$

- Simple coalescence
  - Flat $B_2(p_T)$
  - Simple relationship between d & p v_2:
    - $v_2^d(p_T^d) = 2 v_2^p(2 p_T^p)$
- Simple coalescence does not describe ALICE deuteron measurements in Pb–Pb
  - Describes lower energy A–A data
  - B_2 flatter for smaller collision systems





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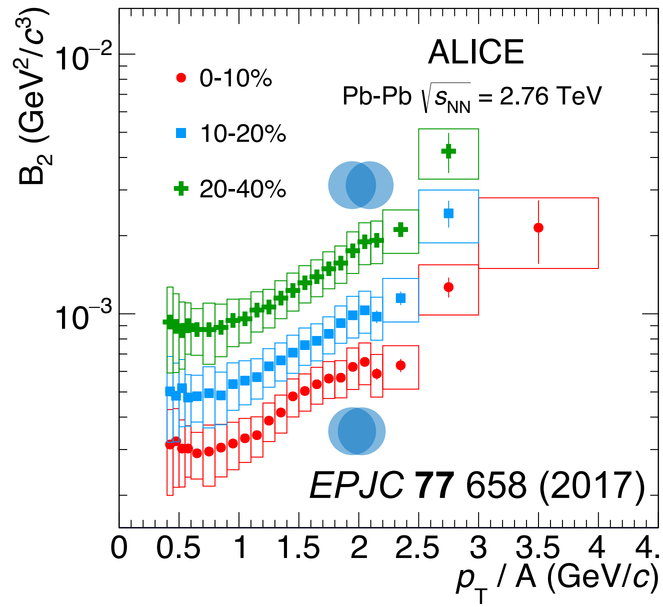

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  - Flat $B_2(p_T)$
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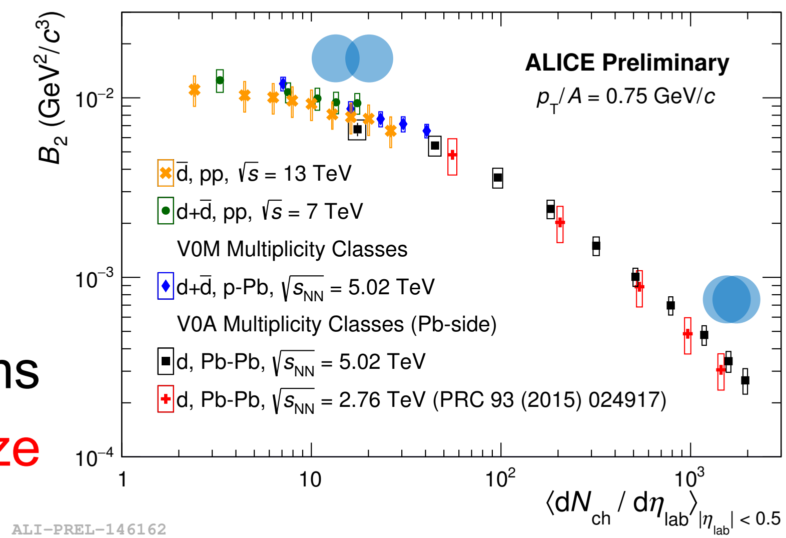
  - Describes lower energy A–A data
  - B_2 flatter for smaller collision systems
  - B_2 evolves smoothly with system size



^{4}He and Hypertriton

- Measurements of ^{4}He, $^4\overline{\mathrm{He}}$, $^3_\Lambda$H, & $^3_\Lambda\overline{\mathrm{H}}$ in Pb–Pb collisions
  - Yields well described by thermal models
  - Exponential decrease in (anti)nucleus production (vs. mass)
- Hypertriton lifetime: new measurement consistent with world average and also free Λ lifetime

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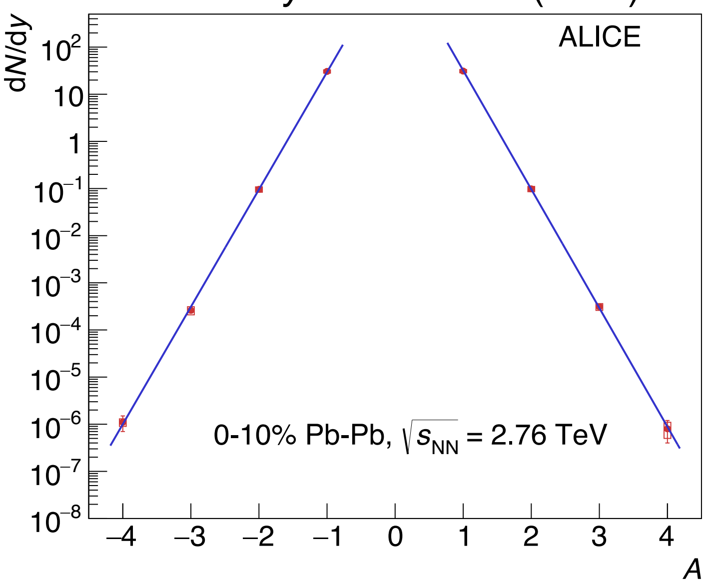
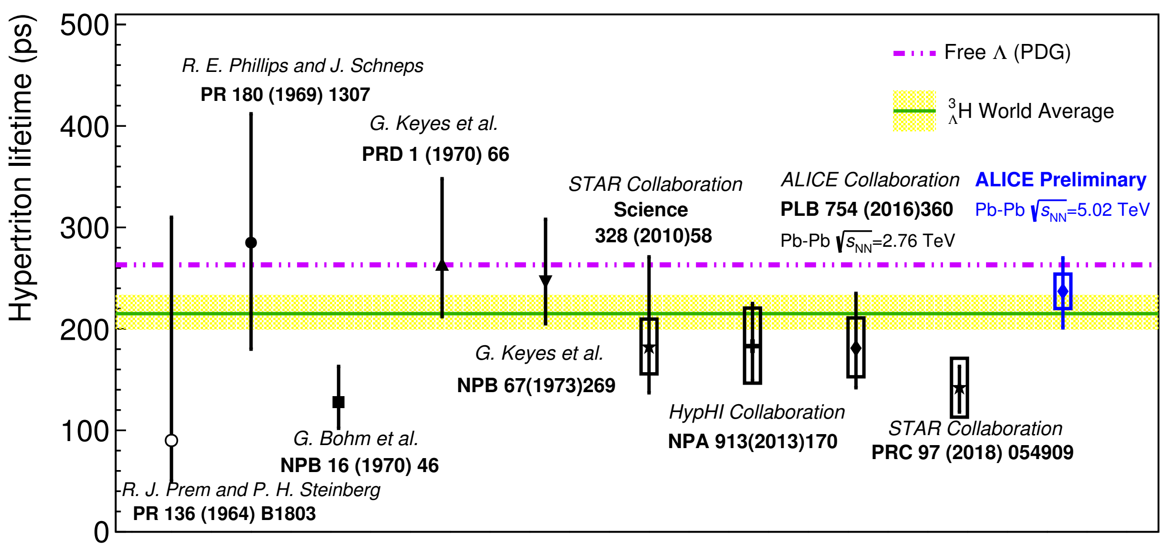
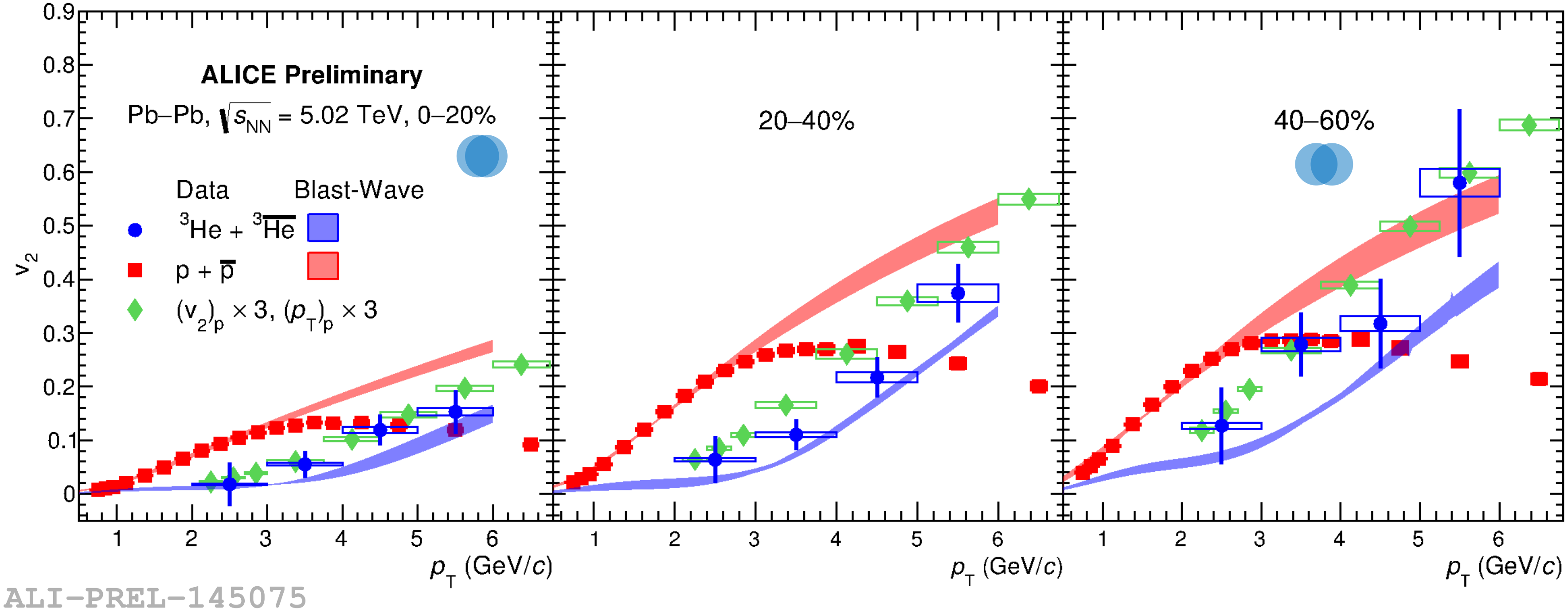




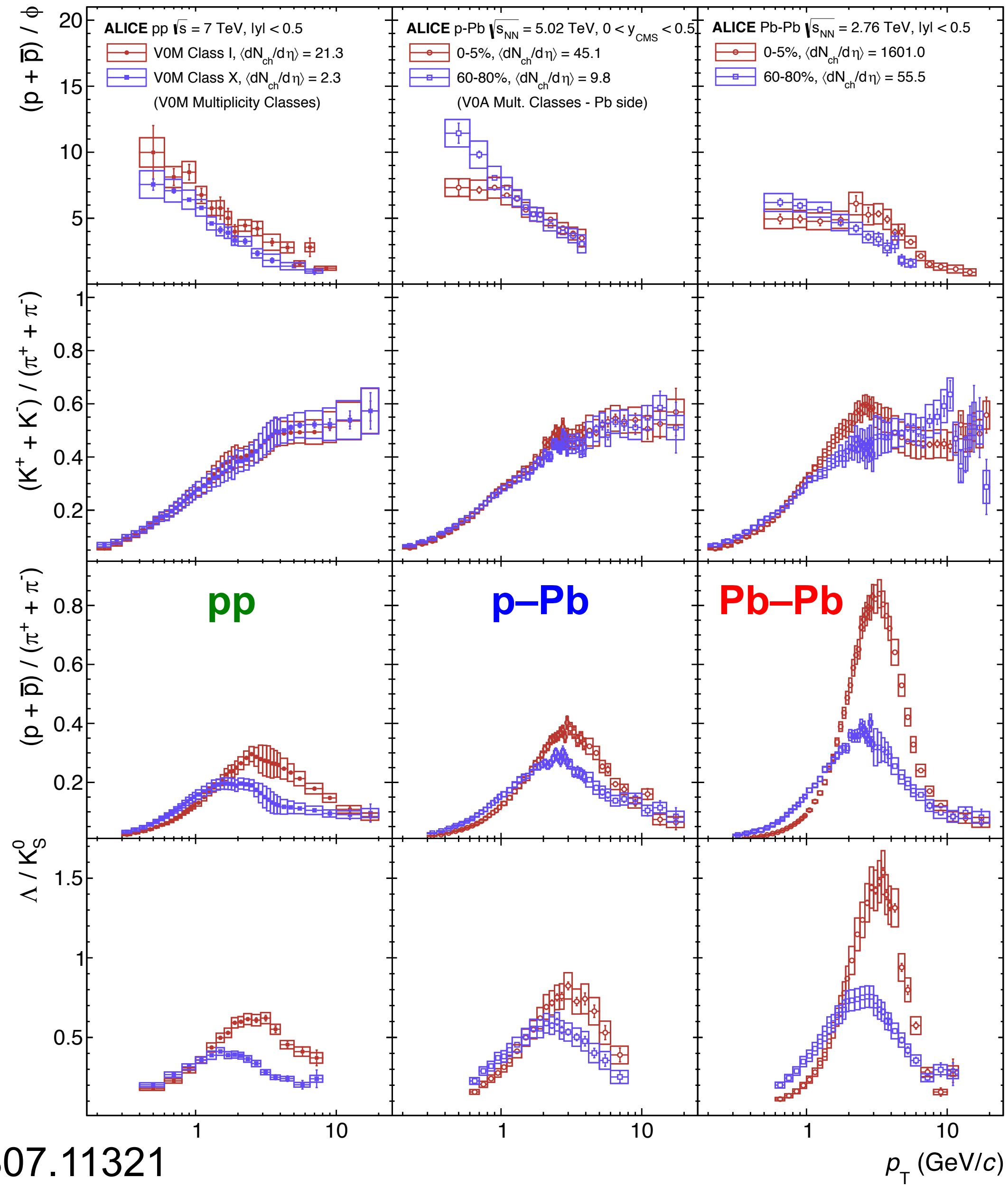
ALI-DER-161043

^{3}He Flow

- ^{3}He v_2
  – Not as well described by blast-wave as d and p
  – Well described by coalescence for central Pb–Pb



Baryon/Meson Ratios



arXiv:1807.11321

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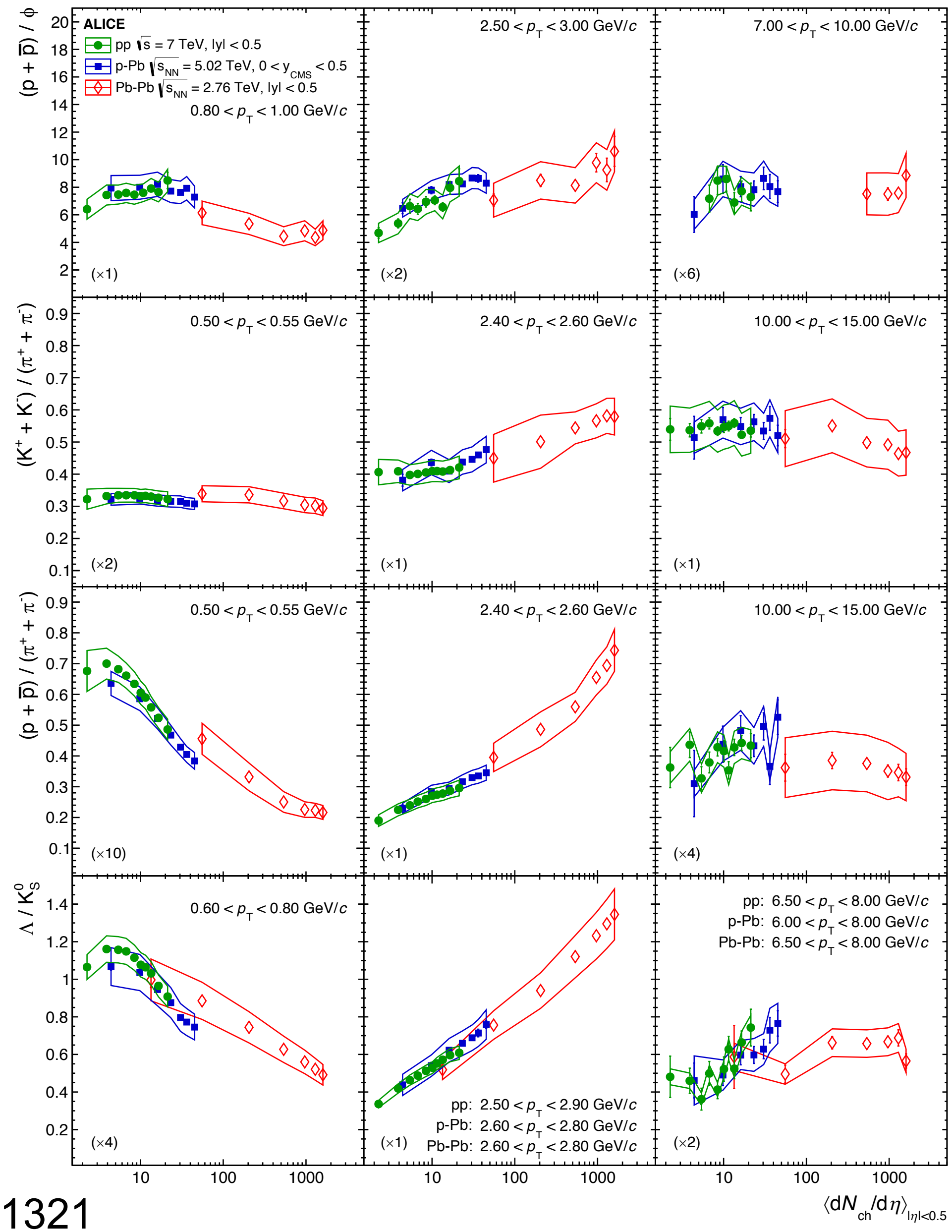

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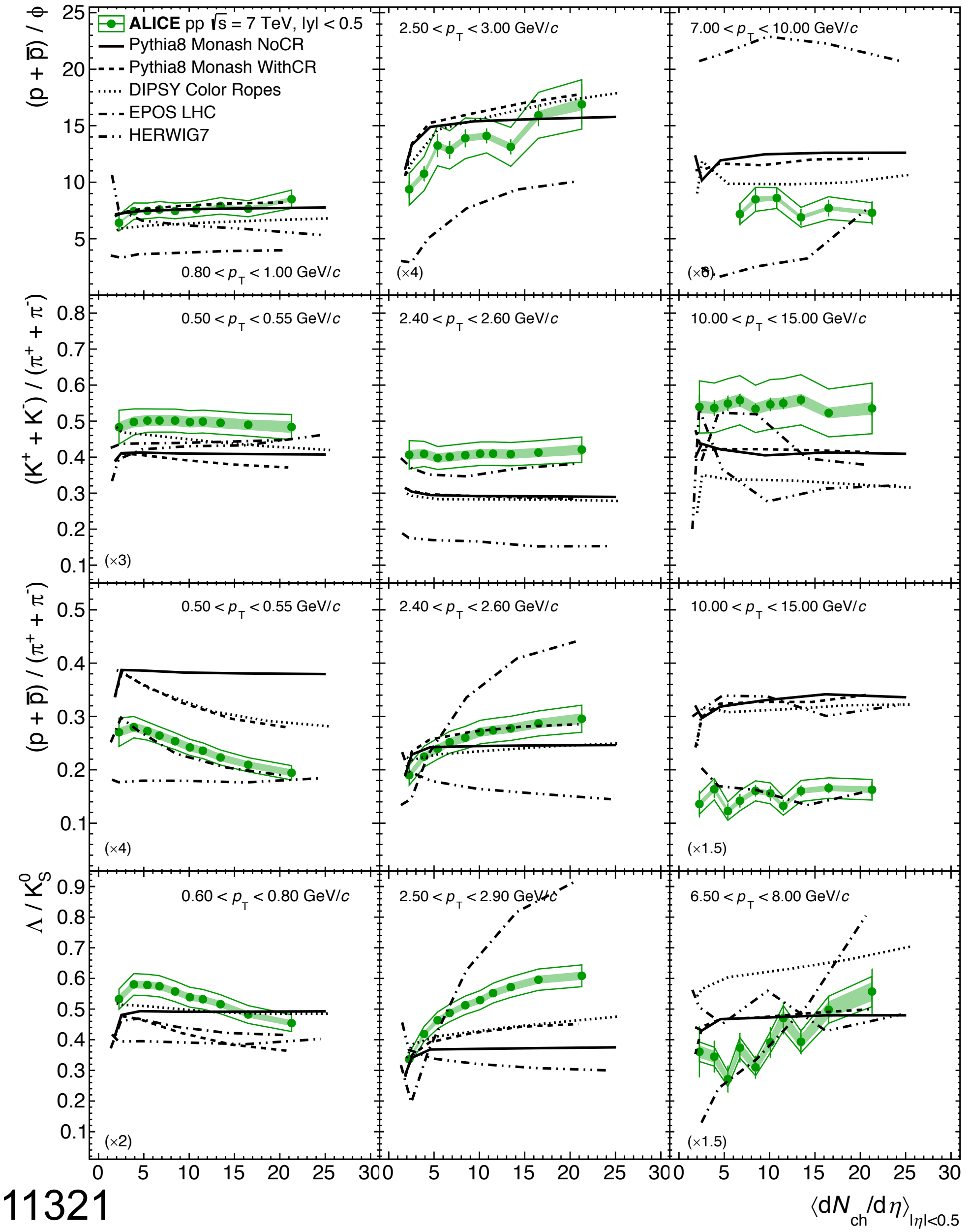

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